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# Carbon sequestration by forestation across China: Past, present, and future

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ABSTRACT

Plantation forests are the most effective and ecologically friendly way of absorbing $CO_2$ and increasing carbon sinks in terrestrial ecosystems; mitigating global warming and beginning ecological restoration. China's forestation rate is the highest in the world, and contributes significantly to the nation's carbon sequestration. We have applied empirical growth curves, scale transformations, field sampling plots, and forest inventory data, to our carbon estimation model, to analyze the carbon sequestration in living biomass and soil organic carbon pools in past and current plantations. Furthermore, the potential carbon sinks of future plantations, 2010–2050, have been simulated. From 1950 to the present, plantations in China sequestered 1.686 Pg C by net uptake into biomass and emissions of soil organic carbon. The carbon stock of China's present plantations was 7.894 Pg C, including 21.4% of the total sequestration as forest biomass and 78.6% as SOC. We project that China's forestation activities will continue to net sequester carbon to a level of 3.169 Pg C by 2050, and that carbon stock in plantations will amount to 10.395 Pg C. Spatial patterns of carbon sequestration were dissimilar to those of planting area. On the basis of area, carbon sequestrations were highest in North China, while changes were generally greatest in the Northeast and Southwest regions.



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## 1. Introduction

Global climatic warming and rapidly increasing $CO_2$ concentrations, primarily resulting from anthropogenic activities and land use changes, have led to growing concerns about measures for energy saving, emission mitigation, and carbon sink enhancement. Gaining new carbon through forestation has become the most effective, hopeful, and ecologically friendly measure to enhance carbon sequestration in terrestrial ecosystems and mitigate increasing $CO_2$ concentrations in the atmosphere. Large scale forestation will establish large areas of new vegetation to enhance carbon sinks, conserve soils, and improve water quality [1–3]. Forestation is also the primary driving force for transformation between carbon sinks and sources [4–9]. Tree plantations allow the carbon to be sequestered in biomass, thus playing a vital role in the terrestrial carbon sink [3,10–14]. Sequestering carbon in the soil, ultimately as stable humus, may well prove a more lasting solution than temporarily sequestering it in biomass [2,3,15]; soil sequestration would be the most effective in mitigating climatic warming in the long term. However, like any large-scale land use change, plantations can have unintended environmental and socioeconomic impacts that can jeopardize the overall value of carbon mitigation projects [1,16].

Previous investigations have touched upon carbon sequestration as well as changes in forest ecosystems on national, regional, or plot scales [17]. Woodbury et al. [18] estimated that forestation caused sequestration averaging 17 Tg C $year^{-1}$ in the USA between 1990 and 2004, including 6 Tg C $year^{-1}$ in the soil and 11 Tg C $year^{-1}$ in the forest floor. Fang et al. [8] estimated that planted forests sequestered 0.45 Pg C between the mid-1970s and 1998, and that the average carbon density increased from 15.3 to 31.1 Mg C $ha^{-1}$. Liu et al. [19] pointed out that 21.3 Tg carbon was sequestered in new plantations in China under the Natural Forest Conservation Program between 1998 and 2004. Reviews have shown that carbon biomass is influenced by forest type, climate, soil, topography, and human activity [20]. However, the changes in soil organic carbon (SOC) that follow forestation are still under debate, and are influenced by vegetation production, soil conditions, land use history, the type of forest established, and forest management [21]. SOC after planting may increase [22,23] or decrease [12,14,21,24]. However, most reviews have presented initial losses in SOC, followed by slight increases [20,23,25,26]. Potential carbon sinks of forestation at regional or global scales have also been estimated. Global afforestation and reforestation have the potential to sequester 60–90 Pg C between 1995 and 2050, according to Land Use, Land-Use Change and Forestry (LULUCF) reports [27]. Niu and Duiker [28] predicted that carbon sequestration on the marginal croplands of the midwestern USA would be 508–540 Tg C over 20 years, and 1018–1080 Tg C over 50 years, following forestation; this could offset 6–8% of current $CO_2$ emissions. Xu [29] calculated that about 9.7 billion tons of carbon would be sequestered under perpetual rotation, if the total land available (1.3 billion ha) in China were afforested. Chen et al. [30] showed that the potential carbon sequestration by grain, under the Green Program in Yunnan Province, will increase carbon in that province by 49.92–56.62 Tg by 2050; this amounts to 10.82–12.27% of the provincial forest carbon stocks of the 1990s.

However, little research has focused on carbon sequestration of the large scale tree planting programs in China. The absorption of $CO_2$ by plantations is even less well known and remains unclear. Preserved plantation area in China is $0.617 \times 10^8$ according to the Seventh National Forest Resources Inventory 2004–2008; accounting for one third of the plantation area in the world. Plantations have contributed significantly to carbon sequestration in China, and will continue to do so. With gradually expanding area and increasing forest age, it is timely to investigate annual variation in the carbon sink functions of plantations. Our purpose is to analyze the carbon sequestration in the living biomass and the soil organic matter induced by forestation in China, in the past and present, and also to simulate the carbon sink potential of future plantations.

## 2. Materials and methods

Carbon sequestration and the potential of plantations are expressed as carbon stock changes in tree biomass and soil organic matter. Although carbon stock in dead organic matter (litter and dead wood) increases after forestation on cropland or barren land, we have not estimated its changes due to unavailable data and lower change rates relative to living tree biomass. We have developed empirical growth curves for different tree species in each region, based on data from the sampling plots of the National Forestry Inventory. These data were used to estimate carbon sequestration in the tree biomass pools including basic wood density, biomass expansion factors, and carbon fractions. SOC change factors were introduced to estimate the stock change in SOC pools. Terrestrial China was divided into seven regions (Fig. 1 and Table 1) following the scheme of the Chinese Natural Regionalization. These are Eastern China (EC), Northeastern China (NE), Northern China (NC), Southern China (SC), Southwestern China (SW), Northwestern China (NW), and the Tibetan Plateau (TP).

### 2.1. Forestation data

#### 2.1.1. Past forestation

The planted area of each region in China between 1950 and 2010 was collated from the Yearly Forestry Reports (1949–2009) edited by the Forestry Department of China. Choice of tree species for forestation was therefore based on the dominant plantation species

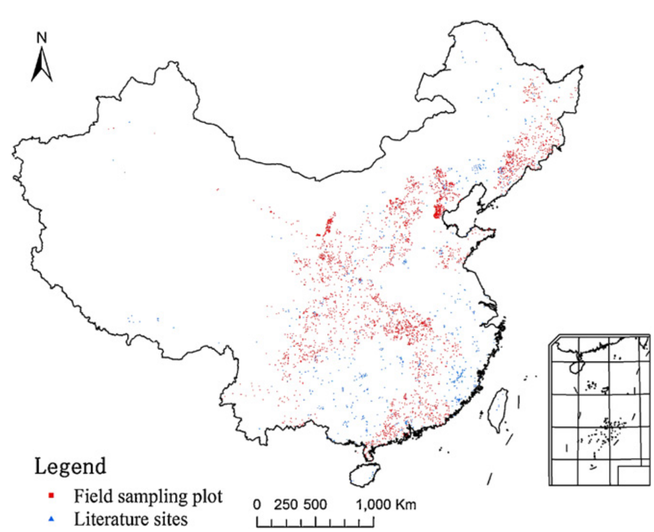


**Fig. 1.** Sites of field sampling plots and data gained from the literature.

**Table 1**
Proportions of species planted in each region.

| Region | Primary planting species | Proportion/% | Region | Primary planting species | Proportion/% |
|---|---|---|---|---|---|
| EC | *Cunninghamia lanceolata* | 44.5 | SC | *Cunninghamia lanceolata* | 32.2 |
| | *P. massoniana* | 15.7 | | *Eucalyptus* | 29.3 |
| | *Keteleeria* | 16.1 | | *Keteleeria* | 12.5 |
| | *Populus* | 11.2 | | *Casuarina equisetifolia L.* | 10.1 |
| | *P. elliottii* | 8.8 | | *P. elliottii* | 6.6 |
| | *Eucalyptus* | 3.7 | | *P. massoniana* | 5.3 |
| NE | *Larix* | 48.3 | | *Picea* | 2.1 |
| | *Populus* | 20.4 | | *Cupressus funebris* | 1.9 |
| | *P. tabulaeformis* | 11.0 | NC | *P. tabulaeformis* | 25.5 |
| | *P. koraiensis* | 8.8 | | *Populus* | 34.7 |
| | *P. sylvestris* | 6.1 | | *Larix* | 15.2 |
| | *Picea* | 4.1 | | *Cunninghamia lanceolata* | 8.7 |
| NW | *Populus* | 85.5 | | *Robinia pseudoacacia L.* | 7.2 |
| | *P. tabulaeformis* | 9.5 | | *Cupressus funebris* | 4.6 |
| | *Picea* | 2.7 | | *Keteleeria* | 2.4 |
| | *Larix* | 2.3 | | *P. armandii* | 1.7 |
| SW | *Cunninghamia lanceolata* | 42.2 | TP | *Populus* | 35.0 |
| | *P. massoniana* | 24.1 | | *Salix babylonica* | 25.0 |
| | *P. armandii* | 14.4 | | *Picea* | 15.0 |
| | *P. yunnanensis* | 7.4 | | *Hippophae rhamnoides Linn.* | 10.0 |
| | *Cupressus funebris* | 6.5 | | *Betula* | 7.5 |
| | *Eucalyptus* | 3.1 | | *Larix* | 7.5 |
| | *Cryptomeria* | 2.3 | | | |

at the time, and planted species were recorded in the National Forest Inventory (Table 1).

### *2.1.2. Future forestation*

Future demand for increasing forest area or coverage and likely tree species have been estimated based on mid-term (to 2020) and long-term (to 2050) national and provincial forest planning strategies. Based on the national target for forest planning up to the year 2050, for example, we have predicted that 301,746 ha of land will be planted between 2010 and 2050, including 113,758 ha of eligible cropland and 187,986 ha of barren land. Furthermore, forest coverage is planned to reach 20.3%, 23.4% and 28% in 2010, 2020, and 2050, respectively. Additionally, the Chinese government has promised that the forest area will increase by $0.4 \times 10^8$ hm$^2$ and the forest stock volume will increase by $13 \times 10^8$ m$^3$ in 2020, from 2005 levels. This was described in the proposed climate mitigation actions that China submitted to the UNFCCC at the 2009 Copenhagen Conference (Table 2).

### *2.1.3. Data from field sampling plots*

Data from sampling plots in plantations at 9078 sites was provided in the National Forestry Inventory, conducted once every 5 years since the 1970s. Recorded parameters include stand volume, tree species, site conditions, age classes, soil depths, and soil types (Fig. 1).

### *2.1.4. Data from the literature*

We collated the measured plantation biomass from 1209 field plots including the spatial distribution and representativeness of each plantation type, from Luo [31], Zhou et al. [32], Shi [33], and Zhao and Zhou [34]. This data covered 36 major tree species representing a wide range of China's plantation types and field site conditions (Fig. 1).

## *2.2. Several assumptions in estimating carbon sequestration*

### *2.2.1. The average growth curves of plantations in each region*

The average growth curves of plantations in each region played a crucial role in our estimation of carbon sequestration in biomass. Growth curves were fitted to the stand volume of established plantations varied with site conditions for each region, and were used to represent mean growth under diverse climates, site conditions, and forest disturbances. Therefore, use of the mean growth curves may have led to overestimation (worse site conditions) or underestimation (better site conditions).

### *2.2.2. Reforestation considering harvest*

Prior to 2000, more than 60–90% of planted forests were commercial plantations, with a regulatory rotation age of less than 30 years following the regulations in the Forest Management Inventory. Since 2000, commercial plantation area has decreased to 46.52% (1999–2003) and then to 35.38% (2004–2008) according to the Forestry Yearbook. Therefore, over 55.07% and 57.06% of

**Table 2**
Governmental planning of future planting, 2000–2050 (km$^2$).

| Region | 2000–2010 | 2010–2015 | 2015–2020 | 2020–2050 | Primary planting tree species |
|---|---|---|---|---|---|
| EC | 69734.42 | 5881.99 | 5881.99 | 12708.27 | *Cunninghamia lanceolata*, *P. massoniana*, *P. elliottii*, *Populus*, *Lauraceae*, *Cryptomeria* |
| NC | 5496.60 | 5496.60 | 32022.30 | 5496.60 | *Populus*, *Cupressus funebris*, *P. tabulaeformis*, *Salix babylonica*, *Robinia pseudoacacia L.*, *P. bungeana* |
| NE | 55441.61 | 15067.02 | 15067.02 | 22545.57 | *Populus*, *Larix*, *Picea*, *P. tabulaeformis*, *Abies*, *P. koraiensis*, *P. bolleana*, *P. sylvestris*, *Cupressus funebris*, *Robinia pseudoacacia L.* |
| NW | 33784.62 | 8763.22 | 8763.22 | 16372.6 | *P. bolleana*, *Ulmus pumila L.*, *Hippophae rhamnoides Linn.*, *Picea*, *P. tabulaeformis*, *Cupressus funebris*, *P. armandii*, *Larix*, *Robinia pseudoacacia L.*, *P. sylvestris* |
| SC | 38173.44 | 4663.34 | 4663.34 | 6252.32 | *Eucalyptus*, *P. massoniana*, *Cunninghamia lanceolata*, *P. elliottii*, *Casuarina equisetifolia L.* |
| SW | 69912.58 | 7411.93 | 7411.93 | 20181.43 | *Cunninghamia lanceolata*, *P. massoniana*, *P. armandii*, *Eucalyptus*, *Cupressus funebris*, *P. elliottii*, *P. yunnanensis* |
| TP | 6569.58 | 4207.48 | 4207.03 | 3452.96 | *Populus*, *Larix*, *P. tabulaeformis*, *Picea*, *Abies*, *Cupressus funebris* |

**Table 3**
Parameters used to calculate the carbon biomass sequestration of plantations.

| Tree species | Growth model | a | b | c | $r^2$ | BEF | WD | CF | MR |
|---|---|---|---|---|---|---|---|---|---|
| *P. yunnanensis* | Logistic | 54.49 | 3.51 | 0.20 | 0.88 | 2.04 | 0.483 | 0.54 | 51 |
| *P. massoniana* | Korf | 116.42 | 3.424 | 0.430 | 0.64 | 2.13 | 0.542 | 0.52 | 41 |
| *P. tabulaeformis* | Richards | 98.85 | 0.027 | 1.782 | 0.822 | 2.06 | 0.492 | 0.51 | 41 |
| *Larix* | Gompertz | 75.014 | 0.165 | 12.055 | 0.89 | 1.74 | 0.490 | 0.51 | 61 |
| *P. armandii* | Logistic | 69.38 | 2.53 | 0.09 | 0.75 | 2.29 | 0.396 | 0.50 | 51 |
| *P. sylvestris* | Logistic | 151.89 | 3.33 | 0.08 | 0.60 | 2.36 | 0.375 | 0.41 | 41 |
| *P. elliottii* | Richards | 69.18 | 0.09 | 1.22 | 0.60 | 2.13 | 0.542 | 0.52 | 41 |
| *P. koraiensis* | Korf | 113.52 | 9.44 | 0.62 | 0.67 | 2.24 | 0.468 | 0.49 | 61 |
| *Cunninghamia lanceolata* | Gompertz | 149.825 | 1.182 | 0.061 | 0.93 | 1.92 | 0.307 | 0.49 | 36 |
| *Betula* | Korf | 119.58 | 222.14 | 1.61 | 0.69 | 1.62 | 0.541 | 0.50 | 51 |
| *Eucalyptus* | Richards | 85.48 | 0.14 | 2.80 | 0.55 | 1.65 | 0.578 | 0.50 | 26 |
| *Cupressus funebris* | Richards | 36.41 | 0.05 | 1.94 | 0.51 | 2.11 | 0.478 | 0.50 | 101 |
| *Abies* | Richards | 365.18 | 0.02 | 5.04 | 0.71 | 2.12 | 0.366 | 0.49 | 61 |
| *Picea* | Logistic | 184.86 | 4.34 | 0.11 | 0.68 | 2.12 | 0.342 | 0.51 | 101 |
| *Cryptomeria* | Logistic | 48.63 | 3.45 | 0.39 | 0.71 | 1.91 | 0.294 | 0.50 | 36 |
| *Keteleeria* | Logistic | 53.25 | 2.39 | 0.10 | 0.57 | 2.23 | 0.448 | 0.50 | 51 |
| *Lauraceae* | Korf | 100.04 | 17.81 | 0.68 | 0.76 | 1.89 | 0.46 | 0.49 | 71 |
| *Populus* | Korf | 319.61 | 5.06 | 0.33 | 0.59 | 2.16 | 0.378 | 0.51 | 60 |
| *P. bolleana* | Korf | 99.12 | 7.53 | 0.75 | 0.94 | 2.16 | 0.378 | 0.51 | 30 |
| *Salix babylonica* | Richards | 49.05 | 0.25 | 5.41 | 0.71 | 2.31 | 0.465 | 0.50 | 16 |

the later established forests are so-called Ecological Service Forests (noncommercial plantations), that are not allowed to be harvested until over-mature according to the Technical Regulations for Ecological Service Forest. We assumed that plantations would be regenerated after clear cutting when they exceeded a minimum rotation age. It was assumed that all harvested biomass would decompose immediately and all harvested lands would be regenerated immediately after harvest, and that the aboveground parts of all cut trees would be cleared away. We also assumed that the initial volume of soil organic carbon after reforestation was equal to the volume before regeneration. In addition, the carbon sequestration of harvested wood products was not considered. Average minimum rotations were determined in accordance with the primary tree species planted, and the regulations in the Forest Management Inventory (Table 3).

### 2.2.3. Survival rate and area not harvested

We can see that total area of forest planted (2004–2008) has been well exceeded by the current plantation area (61.65% of the established plantation area), and about 40% of the established plantation area has been harvested (Table 4). The contribution ratios of plantation to forest coverage in China (5 or 10 years after planting) were less than 50% [35]. This illuminated the relatively lower survival rate of plantations and the harvesting of commercial stands. According to statistics data from the State Forestry Administration of China, the survival rates of plantings in NC, NE, EC, SC, NW, and TP prior to the 1990s were 40%, 50%, 60%, 75% and 70%, and since then should be over 85%, 70%, 85%, 75%, and 90%, respectively.

### 2.2.4. Soil organic carbon before planting

We adopted soil organic carbon density data from Wang et al. [36] as a baseline for calibration of SOC. The soil organic carbon density data included the physiochemical properties of every soil stratum from 2473 typical soil profiles; these profiles were collected for the Second National Soil Survey of soil subtypes.

### 2.3. Biomass carbon change of forestation

The carbon sequestration change method was adopted following Chen et al. [30] and utilized for the estimation of carbon biomass stocks in living trees. The formula was as follows:

$$CS_i = \sum_i \sum_j \sum_k A_{ijk} V_{ijk} WD_{ij} BEF_{ij} CF_{ij} \tag{1}$$

where $CS_i$ corresponds to carbon sequestration (Mg C) in living tree biomass in region $i$, $A_{ijk}$ represents the corrected area (ha) of species $j$ planted or to be planted in year $k$ in region $i$, $V_{ijk}$ indicates stand volume per hectare ($\text{m}^3\,\text{ha}^{-1}$), $WD_{ij}$ is the basic wood density ($\text{Mg}\,\text{m}^{-3}$), $BEF_{ij}$ is a biomass expansion factor (dimensionless) for conversion of stem biomass to stand biomass (including stems, branches, foliage, and roots), and $CF_{ij}$ is the carbon fraction ($\text{Mg C Mg}^{-1}$) (Table 3). The biomass expansion factor and basic wood density used in the estimate were from the China Initial National Communication. Carbon fractions were derived from the literature. The minimum rotation (MR) periods for major species within Ecological Service Forest are listed in Table 3.

These data represent average growth values of stand volumes under different site conditions and forest management practices. The stand volumes of different tree species in plantations in different regions were fitted against age classes using Matlab software and applying four theoretical growth models (Richards, Korf, Logistic and Gompertz, Eqs. (2)–(5)). The best model was then chosen and used (Table 3).

$$V_{ijk} = a \cdot [1 - \exp(-b \cdot age)]^c \tag{2}$$

$$V_{ijk} = a \cdot \exp\left(\frac{-b}{x^c}\right) \tag{3}$$

$$V_{ijk} = \frac{a}{1 + \exp(b - cx)} \tag{4}$$

$$V = ae^{(-e^{b-cx})} \tag{5}$$

### 2.4. Soil organic carbon change induced by forestation

The organic carbon pool in the soil may be a potential long-term sink following forestation. However, changes in soil organic carbon following forestation vary significantly with the land use/cover types before planting and other bio-physical conditions, and changes are usually non-linear over time [20,37]. SOC stock changes were estimated using the formula:

$$SoilCS_i = \sum_i \sum_j \sum_k A_{ijk} R_i SoilCS \tag{6}$$

where $SoilCS_i$ corresponds to the carbon stock change (Mg C) in the SOC pool in region $i$, $A_{ijk}$ represents the area (ha) of species $j$ planted or to be planted in year $k$ in region $i$, $R_i$ represents the factor of SOC stock change ($\text{Mg C ha year}^{-1}$), and $SoilCS_i$ is the original value of SOC before planting. The decomposition and accumulation rates of

**Table 4**
Plantation variables, 1950–2008.

| Periods | Planting area/$10^6$ hm$^2$ | Plantation area/$10^6$ hm$^2$ | Plantation coverage/% | Forest coverage/% | Plantation without harvest/% | Contribution ratio of plantation/% |
|---|---|---|---|---|---|---|
| 1950–1962 | 34.11 | | 0.53 | 12.70 | | 17.69 |
| 1973–1976 | 56.13 | 28.20 | 2.47 | 12.00 | 7.5 | 35.35 |
| 1977–1981 | 22.44 | 27.81 | 2.31 | 12.98 | 10.47 | 18.34 |
| 1984–1988 | 43.63 | 31.01 | 3.23 | 13.92 | 14.24 | 49.82 |
| 1989–1993 | 27.76 | 33.79 | 3.57 | 15.12 | 14.79 | 44.49 |
| 1994–1998 | 25.29 | 36.42 | 4.86 | 16.55 | 16.55 | 50.24 |
| 1999–2003 | 31.85 | 46.67 | 5.55 | 18.21 | 38.34 | 52.52 |
| 2004–2008 | 20.16 | 61.65 | 10.44 | 20.36 | | 43.47 |

**Table 5**
Parameters used to calculate changes in SOC rates in different regions.

| Region | North | Northeast | South | Central | Southwest | Northwest | TP |
|---|---|---|---|---|---|---|---|
| *a* | 1.07 | 0.94 | 1.50 | 1.26 | 1.35 | 0.89 | 0.78 |
| *b* | 2.78 | 2.50 | 3.10 | 2.94 | 3.00 | 2.20 | 2.00 |

soil organic carbon after forestation varied due to differing regional hydrothermal conditions, rates of tree growth, and rates of canopy closure. The rate of SOC stock change can be fitted following the methods of Post and Kwon [37], Paul et al. [20], and Huang et al. [26] as follows; parameters *a* and *b* for each region are listed in Table 5.

$$R_i = a \cdot \ln \quad age - b \tag{7}$$

## 3. Results

### 3.1. Spatiotemporal variations in forestation in China

Forest coverage and forest area in China have decreased since 1950 and then tended to increase after the 1970s as a result of massive forestation campaigns, referred to as the largest land-use change projects in China. Plantings between 1950 and 2009 totaled about $130.09 \times 10^6$ hm$^2$ in area, and annual planting areas averaged $2.17 \times 10^6$ hm$^2$, ranging from a minimum of $0.34 \times 10^5$ hm$^2$ in 1950 to $9.12 \times 10^6$ hm$^2$ in 2003. Plantation coverage increased from 0.53% in 1950 to 10.44% in 2008 (Fig. 2). However, the plantation area in existence was only $61.65 \times 10^6$ hm$^2$ at present (Table 4), indicating a very low survival rate and the cutting of plantations for timber. We have predicted that $21.65 \times 10^6$ hm$^2$ of land will be planted in China between 2010 and 2050. Our estimate of annual area planted during this period is outlined in Table 2.

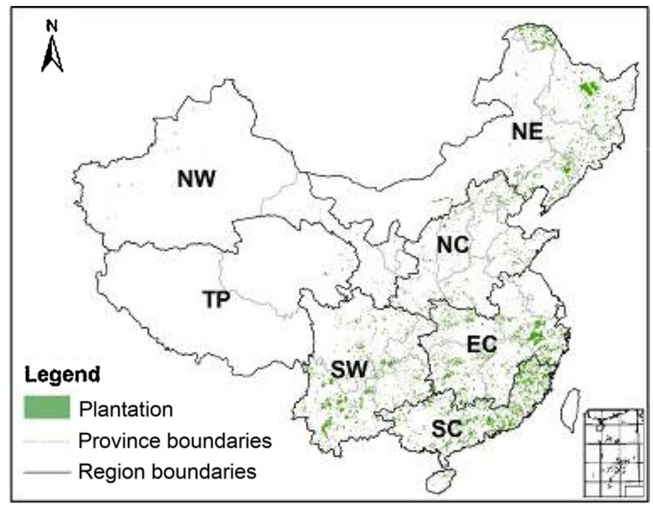


**Fig. 2.** Distribution map of plantations.

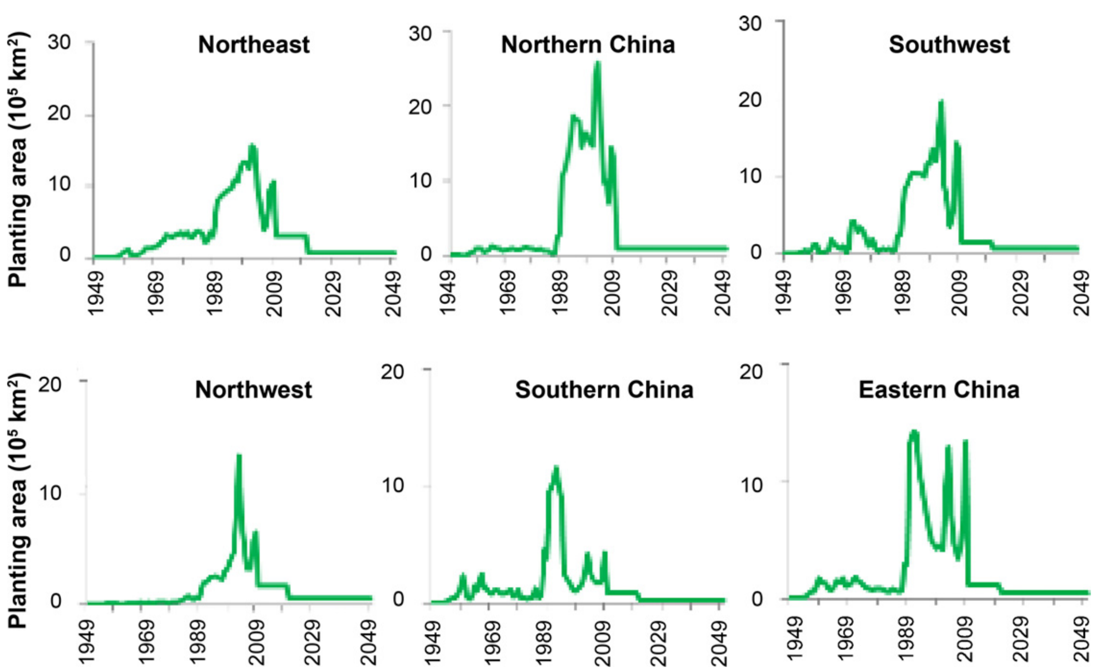


**Fig. 3.** Annual forestation areas between 1950 and 2009.

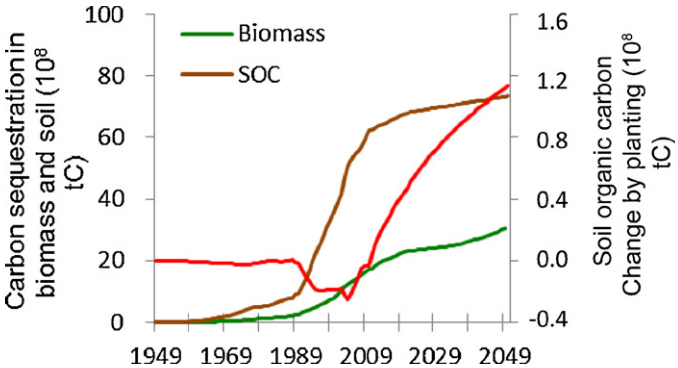


**Fig. 4.** Annual carbon sequestration of forestation between 1950 and 2050.

Between the 1950s and 1960s, forestation focused on the planting of timber plantations. More than $7.09 \times 10^6$ hm$^2$ of plantations were established, with an annual average area of $0.36 \times 10^6$ hm$^2$. In the 1970s, the Three-North Shelter Forest Program and the Plain Greening Project were launched, and aerial seeding was used. The annual average area of newly planted forests increased to $0.84 \times 10^6$ hm$^2$, more than four times the previous rate. In the 1980s, economic plantations and orchards (including palm oil, rubber, and coconut) reached nearly one billion hectares in area; the annual average planting area was $0.822 \times 10^6$ hm$^2$. From the late 1990s to 2009, six key forest projects were begun, including the Natural Forest Protection Project and the Green for Grain Project. The increased average planting area was $5.32 \times 10^6$ hm$^2$ per year, with a total of $106.31 \times 10^6$ hm$^2$.

The largest area of planting has been in Northern China. This accounts for 25.19% of the total in China. Primary tree species were *P. tabulaeformis*, *Populus*, *Larix* (Table 1). Much of the remaining (21.57%) planting occurred in the Northeast region (Fig. 3), with primary tree species *Larix*, *Populus*, *P. tabulaeformis* (Table 1). Southwestern China accounted for 19.35%, and Eastern China for 14.67%. Interestingly, the two regions with opposite climates (tropical and subtropical Southern China, and the arid and semiarid Northwestern) showed similar trends in planting area to the other regions, accounting for 8.98% and 8.57% of the planted area, respectively. The Tibetan Plateau, where planting has been limited by the high-cold conditions, accounted for only 1.67%.

### 3.2. *Carbon sequestration of forestation in China, 1950–2050*

Carbon biomass sequestration, soil carbon changes, and the net budget of China's plantations for the 1950–2050 period are illustrated in Fig. 4. Carbon biomass sequestration has shown continued increase, especially since 2000. However, changes in SOC induced by China's forestation activities showed a decrease until recently, and then an increase. Between 1950 and 2010, total carbon sequestration from forestation amounted to 1.686 Pg C, including 1.689 Pg C sequestered in biomass, and 0.003 Pg C released into the atmosphere by the soil. The SOC storage of plantations totaled about 6.205 Pg C in 2010. The net carbon sequestration in the 1950s was 0.004 Pg C, including 0.005 Pg C in tree growth and 0.001 Pg C in soil carbon emissions. Comparison of net carbon sequestration for the decadal showed that forest carbon sequestration in the 1960s, 1970s, and 1980s were 8.5, 28, and 56 times larger than the baseline in the 1950s. In the 1990s, total carbon sequestration from forestation activities amounted to 0.702 Pg C, including 0.721 Pg C in tree growth and 0.019 Pg C in soil carbon emissions. With an current area of 61.65 M ha, China's plantations presently have a carbon stock of 7.894 Pg C, including 1.689 Pg C in biomass and 6.205 Pg C in SOC, with the net negative change in SOC due to forestation totaling 0.003 Pg C. The average carbon biomass density was 27.397 Mg C ha$^{-1}$, and the average SOC density was 100.65 Mg C ha$^{-1}$.

Between 2010 and 2050, the net carbon sequestration potential from newly planted forests is projected to be 2.51 Pg C, or 24.13% of the total. Under current governmental planning scenarios, the net carbon sequestration of the plantations in China is expected to be 2.077 Pg C by 2015, and 2.327 Pg C by 2020. This would include carbon sequestrations in living tree biomass of 2.052 Pg C and 2.283 Pg C, and in SOC stock changes 0.025 Pg C and 0.044 Pg C, correspondingly. Up until 2050, the net cumulative carbon sequestration from forestation activities in China is predicted to be 3.169 Pg C and the carbon stock in plantations is predicted to amount to 10.395 Pg C, including 3.055 Pg C in biomass and 7.34 Pg C in SOC, with a net change in SOC of 0.114 Pg C (Fig. 4).

### 3.3. *Uneven regional distribution of carbon sequestration*

The carbon sequestration of plantations in the seven regions of China has shown generally similar patterns in net carbon biomass sequestration over time (Fig. 5a), with a net loss of soil organic carbon prior to the 1990s–2000 period, and a gain in SOC following this (Fig. 5b). Following planting, forest biomass dynamics change more quickly than those in the soil. Furthermore, the rate of sequestration is predicted to increase in the future. The patterns of biomass sequestration in the Northeast, Northern, and Southwest regions were different from those in the other regions, with the largest, rapidly increasing rate of biomass carbon sequestration between 1950 and 2050 in the former regions. The effect of forestation in the Northeast was greater than in any other region. The Eastern, Southern, and Northwest of China showed an increasing rate of carbon biomass sequestration; equal to half the largest rate between 1950 and the present. For these regions we have predicted the slowest decreasing rate of continued sequestration through to 2050. Similar trends in SOC in each region, including a steady loss of carbon in the past and then an increase, and differences in change rate and time taken to reach to minimum values, varied from the 1990s to the

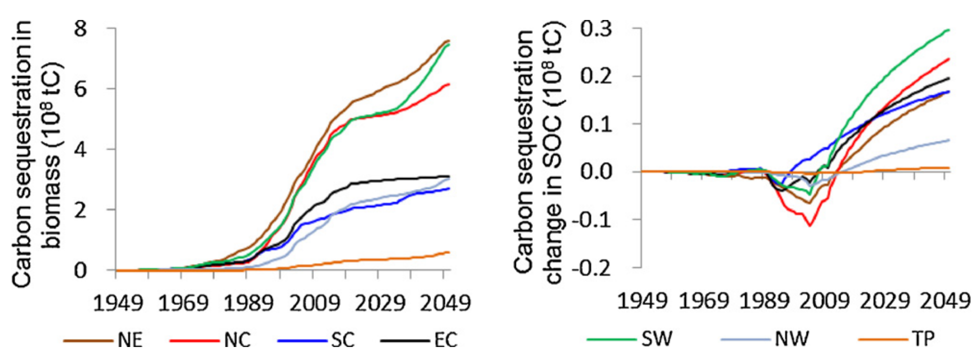


**Fig. 5.** Annual carbon sequestration in biomass (a), and carbon sequestration change in SOC (b), induced by forestation in each region between 1950 and 2050.

present. Unlike in most other regions, there was minimal biomass sequestration and almost no net loss or gain in the Tibetan Plateau during any period. This pattern was due to the slower growth and very low survival rates of plantations in this region.

## 4. Discussion

### *4.1. Uncertainties in estimation of carbon sequestration*

Our effort to estimate plantation carbon sequestration across a wide range of spatial and temporal scales, includes uncertainties from provincial variables, modeling logic, and estimation parameters. Quantifying model uncertainties allows carbon estimates to be reported with known levels of confidence [38,39]. Identifying and minimizing these inaccuracies will improve model predictions. Uncertainty issues in carbon sequestration assessment are starting to be recognized from reserving rather than cutting areas of plantation. Such differences can be considerable and could have significant impacts on carbon sequestration. Uncertainties also arise from the estimated parameters derived from the literature, and from bio-physiological observations, such as survival rates, soil carbon densities, and rates of change of SOC in different regions and age classes. Variation in the rate of change in soil carbon stocks related to surrounding conditions, field sampling, and technical measurements, may cause deviations in modeling. In addition, to gain more accurate estimation, we need to take into account the carbon sequestration of the understory and of harvested wood products; lack of this data may lead to underestimation. However, the carbon in wood products was not considered because it was difficult to know the quantity of wood harvested.

The largest uncertainty in our projections relates to uncertainties about future area and species. Many factors will prevent future forestation including social, organizational, economic, and market-imposed constraints such as population growth, the need for agricultural land, and government policies [10]. Subsequently, large-scale plantations may interfere with other priorities for land use that determine the availability of land, the rate at which plantations can be established, and the long-term sustainability of projects. Land that is suitable for forestation may not actually be available. Once these factors are taken into account, the area of land that will actually be available for plantations is reduced. Furthermore, our current estimation does not consider the impact of climate change on growth and decomposition rates. Previous research and reviews have predicted that the net primary production of our forests would increase under the scenario of increasing atmospheric $CO_2$. Nonetheless, the effects of environmental change on forests in the past have already been accounted for in the inventory data, and so were partially represented in the estimation model. However, our future estimates do not take into account the impacts of climate change.

In addition, any simplified estimation generally ignores the impacts of disturbances and the stochastic process of recovery [18,40,41]. Therefore, the effects and mechanisms of stress or disturbances on forest carbon cycling need to be urgently addressed in estimation and assessment of the carbon sink of forest ecosystems. We have raised some questions and concerns. How does varying plantation management impact the forest carbon cycle? Also, the forest carbon feedback loops following natural disasters such as fires, snowstorms, insects, earthquake, or tsunami are rarely able to be observed.

### *4.2. Trade-offs between carbon sequestration and other ecosystem services*

Carbon sequestration strategies have highlighted tree plantations without considering their full environmental consequences. Although sequestering carbon in forests is good for the climate, other outcomes such as loss of biodiversity and local incomes, decreased food security, decline in soil fertility, reduced stream flows, and increased fires and insects may result. Forests also affect the biophysical properties of the land surface, such as the sunlight reflectivity (albedo) and evaporation rate; with further implications for the radiative forcing of climate. The co-benefits and trade-offs of plantations need to be taken into account when negotiating exchange agreements. Joint use of carbon sequestration and the provision of forest-derived products (e.g. timber and biomass for energy) will optimize the contribution of forestry in climatic mitigation. This is particularly attractive in temperate regions where land availability is limited by high land prices and strong competition with other land uses. Well-directed carbon sequestration projects, therefore, that also provide sustainably produced timber, fiber, and energy, will yield numerous benefits, including additional income for rural development, prospects for conservation and other environmental services, and support for indigenous communities. Principles of sustainability must govern the resolution of trade-offs that may arise from ancillary effects in order to simultaneously maximize climate change protection and sustainable development [16].

Furthermore, we need to consider suitably adapted tree species for particular land types, especially degraded land. Hence, a careful choice of tree species used for the forestation occurring under the Kyoto protocol is needed to promote long-term climate change mitigation [2]. Reliable and reasonable forest management patterns and restoration projects, such as selective harvesting, returning residues to land, reducing human disturbance on soils, choosing nitrogen-fixing tree species, fertilizer application, planting of mixed forests, and fire prevention are also important. In addition, land use changes have been driven by social and economic conditions, and to use land purely for the purpose of carbon sequestration is impracticable. Therefore, comprehensive land use planning is necessary, including consideration of biological, economic, and social effects.

### *4.3. Enhancing plantation management*

If China is to be the country with the maximum preserved area of plantation and largest annual planting area, urgent needs are to increase the quantity and enhance the quality of plantations by suitable forest management. Suitable measures for forest management must follow regional conditions [42]. Major strategies available to mitigate carbon emissions through forest management include increasing forest area through reforestation; increasing carbon density of existing forests at stand and landscape scales; expanding the use of forest products that sustainably replace fossil-fuels; reducing emissions from deforestation and low-impact harvesting [16]; increasing productivity by nutrient management, thinning, optimization of rotation time and species; increasing carbon sequestration by residue management, and better utilization of products from thinning.

Quantifying the sources and sinks of carbon resulting from forest management is essential for accurate estimation of national carbon fluxes, and is also helpful in meeting the greenhouse gases emission reduction targets [43]. Although the climate protection role of forests is in no doubt, there are many complexities involved in determining how much of the forest carbon sinks can be managed to mitigate atmospheric $CO_2$ buildup, and in what ways [16]. Furthermore, external factors such as high temperatures result in reduction of the carbon sink, and lead to much higher $CO_2$ concentrations than expected. Forest management therefore becomes a controversial issue if we want to solve the increased terrestrial carbon sources and decreased carbon sink [44–46]. Forest carbon management raises some interesting questions. Is carbon

management compatible with utilization of forest resources? How does carbon management enhance or detract from other ecosystem services such as water conservation and biodiversity [42]?

## 5. Conclusion

During the entire 1950–2050 period, the effects of forestation on biomass carbon pools were greater than the effects on soil carbon pools. Carbon biomass sequestration showed continual increase, however, SOC first decreased and then increased. Forestation caused net carbon sequestration of 1.686 Pg C from biomass and soil organic carbon until the present, and many projects continue this net sequestration into the 21st century. In summary, there remain many uncertainties in our estimates of net carbon sequestration in China's plantations. Despite these uncertainties, it is clear that forests, especially plantations, account for most of China's terrestrial carbon sink. Although not all sources of uncertainty have been fully quantified, our results suggest that statistics-based estimates may have substantially smaller uncertainties than those based on forest carbon modeling. The improved inventory-based estimates of forest carbon stocks presented here, and future refinements of these and other statistics-based estimates, should help to constrain projections from ecological modeling.

Most estimates of forest carbon stocks have neglected or seldom considered the effects of stand age. However, stand volume varies with tree species, site conditions, age classes, and forest disturbances. Young and middle-aged forest accounts for 67.85% of forests in China. The carbon budget of young or mature forest would be under or overestimated if the same parameters are applied without consideration of the impacts of forest age on stand biomass, production, and carbon sequestration. Therefore, we used methods that analyzed the carbon dynamics of different age-classes, to model the carbon sequestration of plantations, and the applicability or not of each parameter were considered. Besides deepening our understanding of increasing carbon sinks by forestation, the limitations and negatives of forestation projects should be realized, and new technologies for forestation and enhancement of carbon stocks should be exploited.

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